Space Nuclear Power Sources

(focus on radioisotope devices)

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Space NPS Seminar, EC JRC ITU
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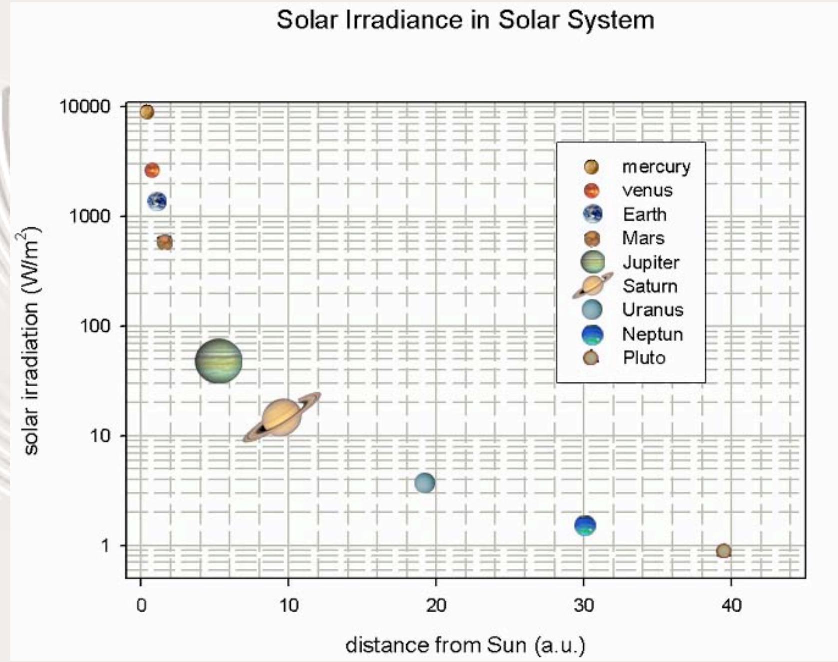
Outline

- **What are space NPS?**
- **International Situation: *Status quo* and Plans**
  - US Situation & NPS devices
  - RU Situation & NPS devices
  - Others
- **European Situation**
  - At national level
  - Defence sector
  - ESA
- **NPS and Planned European Exploration Missions**
- **Potential role of EC JRC**

1.1 Why Nuclear Power in space?



1.2 Subject of Discussion

- **"Space nuclear power source" is the overarching term for**
  - space nuclear reactors (1 available flight proven system (R), 5-6 kWe)
  - radioisotope sources (heating units, thermoelectric generators)
    - flight proven US system (GPHS RTG, 44 launched on 25 missions, 300 We)
    - small Russian system (some We)
- **Space reactors are small fission reactors, using the fission heat to generate electricity (nuclear electric systems) or heat up directly propellant (nuclear thermal propulsion).**
- **Radioisotope systems use the natural decay heat of radioactive isotopes as such or to converted it into electricity.**
- **"Nuclear Propulsion" is the overarching term for**
  - Nuclear electric propulsion (NEP) systems
    (nuclear generated heat-electricity-electric thrusters)
  - Nuclear thermal propulsion (NTP) systems
    (nuclear generated heat-direct propellant acceleration)

2.1 International Situation: *US*

- **Current Status – US situation**
  - Early decision in favour of RTGs
    first system flown in 1961, 44 RTGs flown on 25 missions;
  - One flown small reactor system (1965, operated for 43 days);
  - Cyclic interest led to considerable investments but after 1965 to no further reactor flight model
    ~0.5 $B\$_{1990}$ for SP-100 reactor;
    inventory of subcomponent developments available;
  - Large nuclear thermal propulsion project (NERVA); 1960s (end: 1972/73) large total investment (initially mainly defence related, Mars mission)
  - Closure of Pu-238 production facility (Savannah River Site) in 1980s
    NASA missions rely on Russian Pu-238 (agreements 1992-2002, 2004-2009)
    US inventory reserved for national security applications

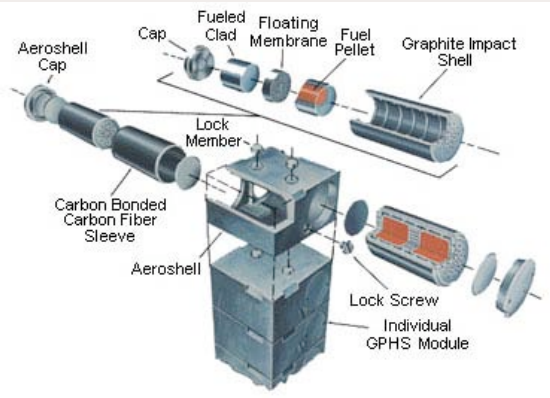
2.2. International Situation: US

- **Current and past US NPS devices: 1965 reactor**

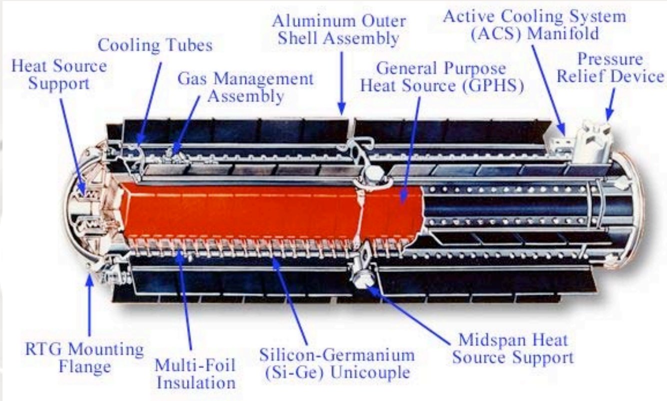


2.3 International Situation: US

Current and past US NPS devices: RTG, RHU



General Purpose Heat Source (GPHS)



General Purpose Heat Source integrated into Radioisotope Thermal Generator (RTG)

GPHS:

thermal power @BoL:	~220-240 W
Mass:	1.45 kg
Dimensions:	9.32x9.72x5.31 cm
PuO2 mass:	~0.6 kg

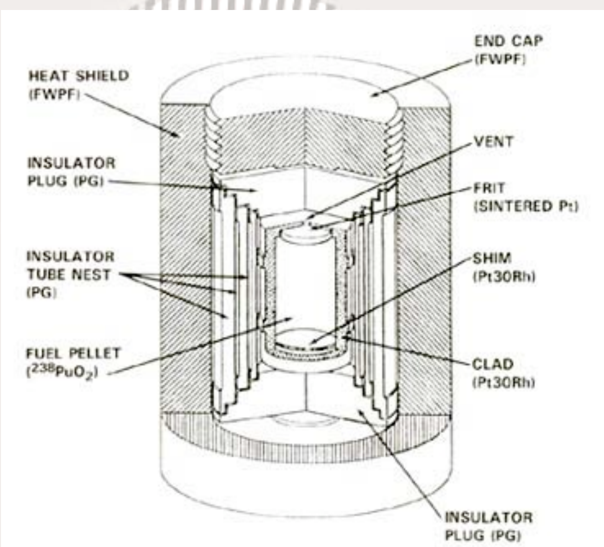
RTG:

Thermal power BoL:	~4264 W
Electric Power BoL:	~285 W
Mass:	56 kg
Dimensions:	114 cm / 42 cm
PuO2 mass:	~10.8 kg

Images: NASA, DoE

2.4 International Situation: US

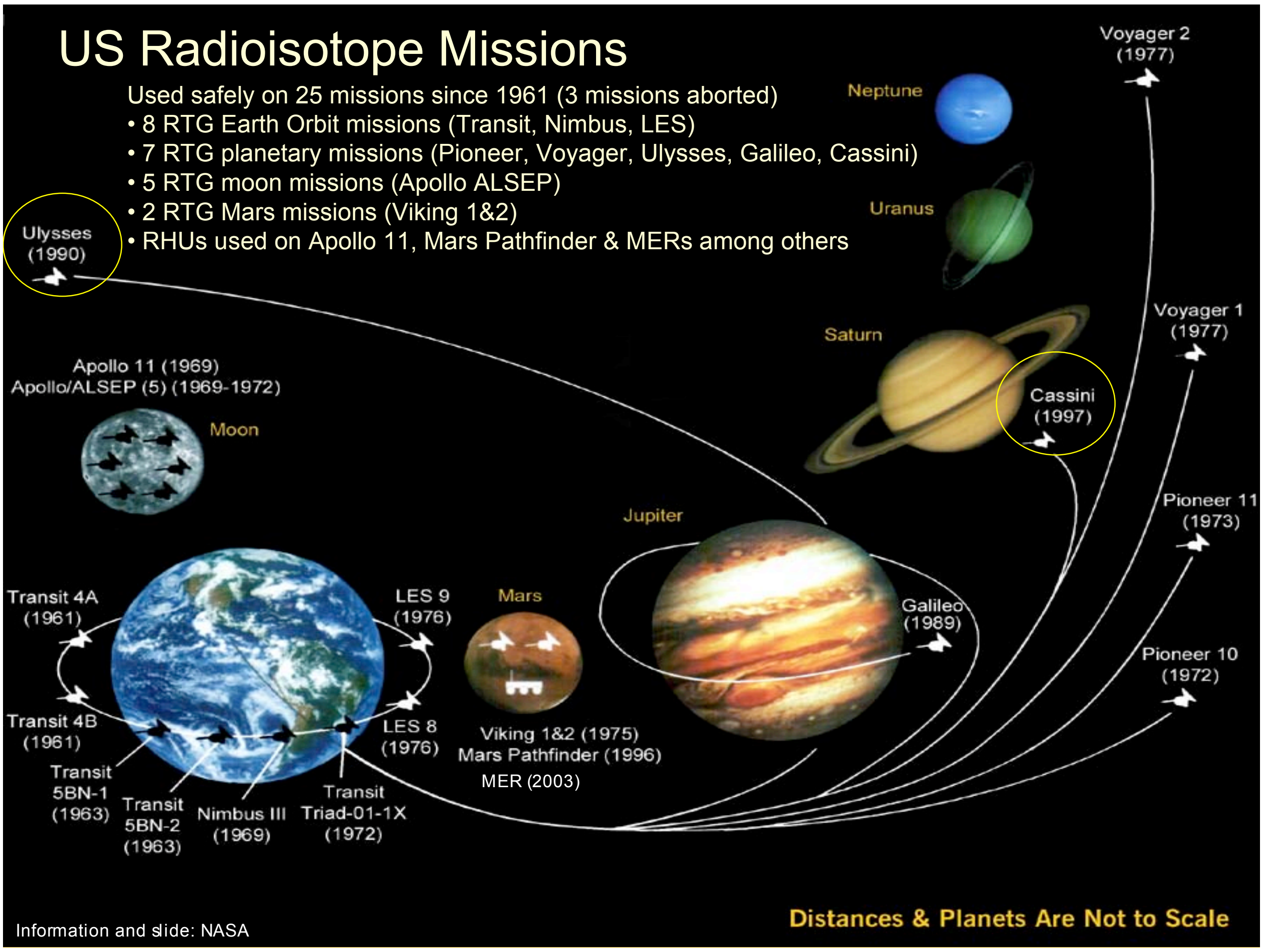
Current and past NPS devices: RHU



RHU: ~2.7 g PuO2
Platinum-30 Rhodium alloy

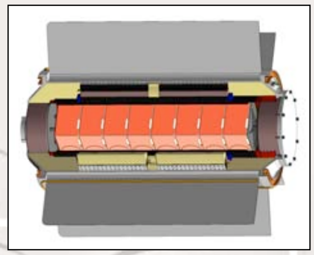
RTG - fuel composition

Fuel component	weight % at launch	$T_{1/2}$ (years)	Bq/g	Bq/RTG
^{236}Pu	0.000001	2.851	2.0×10^{13}	2.2×10^{09}
^{238}Pu	70.810000	87.750	3.6×10^{11}	4.8×10^{15}
^{239}Pu	12.859000	24131.000	2.3×10^{09}	3.2×10^{12}
^{240}Pu	1.787000	6569.000	8.4×10^{09}	1.6×10^{12}
^{241}Pu	0.168000	14.400	3.8×10^{12}	6.9×10^{13}
^{242}Pu	0.111000	375800.000	1.5×10^{08}	1.8×10^{09}
other	2.413000			
Oxygen	11.852000	NA	NA	
total	100	NA	NA	4.9×10^{15}

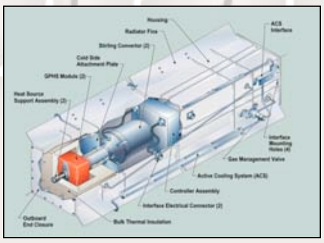


2.3 International Situation: *US*

- **Project Prometheus (bis):**
  - RTGs:
    - Multi Mission RTG (MMRTG)
      contract awarded to *Boeing* (*Boeing Rocketdyne* + *Teledyne Energy Systems*);
      14 years lifetime, 3 years on Mars, space and planetary use; Martian rover, 110 We; 24-34 kg; TE system, ca 4 kg Pu-238,
    - Stirling Radioisotope Generator (SRG)
      contract awarded to *Lockheed Martin* (+ *Stirling Technologies* and GRC),
      114/93 We, 27kg, fourfold reduction of Pu-238 need (1.2kg)
    - Power conversion technology:
      Competitively selected 10 contracts (50 M$ total, 3 years) awarded



MMRTG



SRG

2.4 International Situation: *US*

- **Project Prometheus (bis):**
  - Reactor research – JIMO:
    - Reactor concept screening activity finished by DoE
    - Power conversion by NASA: 3 competitive contracts awarded
    - 3 competitive 10-month contracts awarded to industry for study of JIMO mission proposals (Boeing, Lockheed Martin, Northrop Grumman): (50 M$ each)
    - Naval Reactors responsible for nuclear core (currently different responsibility for conversion system!)

Artist impression of JIMO spacecraft (NASA)

2.5 International Situation: *US*

Plans

- 2.7 B$ to be spent in 2004 – 2007 (680 M$ annual average)
- **Reactor development - JIMO:**
  - 3 competitive 50 M$ studies to be finished on 2004
  - non-nuclear testing at MSFC (Early Flight Fission Test Facility); two main systems studied:
    - Direct Drive Gas Cooled Reactor (DDG), Sandia design, fast spectrum U-235, noble gas
    - Safe Affordable Fission Engine (SAFE), LANL design, fast spectrum U-235, heat pipes
- **RTGs: (estimated down selection for SRG and MMRTG: 12/06)**
  - SRG: qualification unit: 12/05
    Flight units: #1: 11/07, #2: 04/08, #3: 09/08
  - MMRTG: qualification unit: 06/06
    Flight units: #1: 02/08, #2: 08/08
- **Pu-238 production line:**
  - *"Record of Decision"* signed in January 2001 for the "*reestablishment of a domestic production capacity to produce 2 to 5 kg [of Pu-238] per year*"
  - Production line installation takes 5-6 years, total cost ~76 M$ (extracted form presidential budget requests), final decision not taken as by July 2003

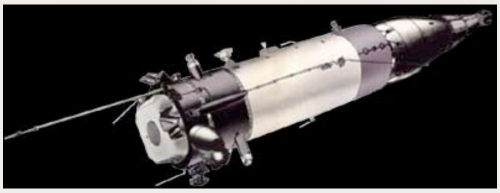
2.6 International Situation: *US*

- **Attempt of an analysis**
  - Technical and institutional capacity ✓
  - Pu-238 national production facility re-establishment start due by 2004/05 for national security purposes
  - Scientific exploration only justification for (high) development effort?
    - Presence of strong national security interests/applications
  - Signs for sustained efforts
    - Navy personnel involvement, clear objective (JIMO) and timeline
    - NASA commitment *before* any DoE commitment
    - No nuclear fuel development – realistic budgeting
  - Parallel industry contracts increase cost

2.7 International Situation: *RU*

- **Current Status – Russian situation**
  - Early decision in favour of fission reactors
    35 reactors launched (mostly ocean reconnaissance missions);
  - Few RTGs
    based on Po-210 for *Lunakhod* missions;
    Small Pu-238 RTGs for *Mars96* mission;
  - Large nuclear thermal propulsion programme – no launch
    test sites (partially?) intact
  - Ongoing Pu-238 production facility
  - Programmes stopped since 1 decade
    Aging workforce – institutional competence?
  - TOPAZ II models sold to US in 1992 for potential cooperation

Mars96 (1996)



Topaz-1 spacecraft (1987)

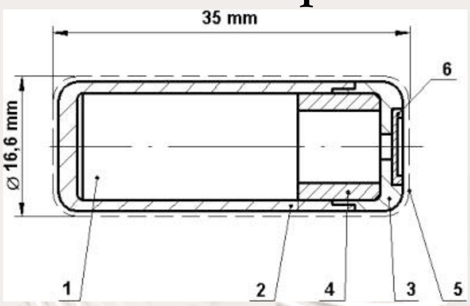
2.8 International Situation: *RU*

- **Currently most relevant available components:**
  - TOPAZ fission reactor (including associated subsystem technology, e.g. high temperature materials, large crystal growth technology; and 20 years development experience);
  - Mini-RTGs and the Pu-238 production capacity;
  - Nuclear test facilities.
- **Flight-proven systems**
  - 33 Bouk/Romashka reactors (RORSAT ocean radar surveillance satellites).
    - 100s-We; fast neutron core, ; 20-25kg U-235 (90%); NaK cooling; thermoelectric conv.; reactor mass 390kg (excl. cold source); last launch 1988.
  - 2 TOPAZ-1 (1987: Cosmos 1818; 1988: Cosmos 1867)
    - 5 kWe, epithermal core, 11.5 kg U-235 (96%); NaK cooling; thermionic in-core conv.; 0.5/1 year operations; reactor mass: 980 kg
    - TOPAZ-2: slight improvements (176 kg/kWe), never launched
- **ISTC Studies (Int. Science and Technology Centre)**

  Two studies most valuable:
  - ISTC-335: feasibility of a NTP development for a lunar tug application and potentially human Mars missions (1996/1997, CEA involvement);
  - ISTC-1172: human Mars mission technology; 3 different nuclear power station designs for Martian surface reactors (100-125 kWe).

2.9 International Situation: Ru

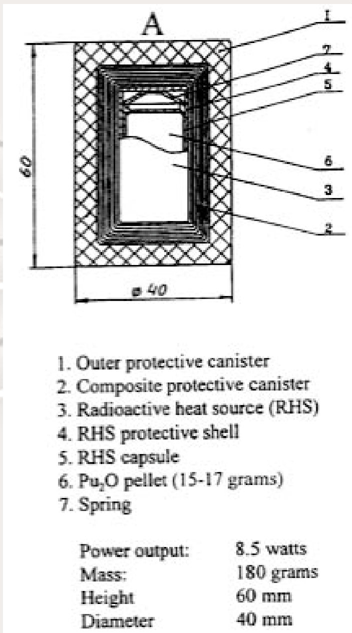
- **Current and past Russian NPS devices: RHU/RTGs**



1) 238Pu clad by iridium and packed into a casing made of a platinum-based alloy
2) protective shell case (tantalum-based alloy)
3) protective shell cover (tantalum-based alloy)
4) plug (tantalum-based alloy)
5) three-layer protective coating
6) membrane (tantalum-based alloy)

RHU (*Pantera*):

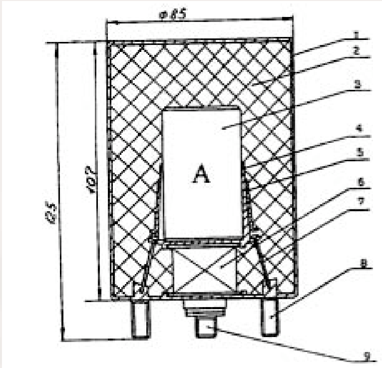
thermal power @BoL:	~8.5 W
Mass:	~0.085 kg
Dimensions:	16.7x35 mm cylinder



2.9 International Situation: Ru

- **Current and past Russian NPS devices: RTG**

	spec. TY 95 11-82 Mark A	spec. TY 95 11-82 Mark B	spec. TT45.T.238-93
^{238}Pu mass fraction (not less)	67	59	74
isotope mass fractions: ^{238}Pu	80	70	85
^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu	20	30	15
^{236}Pu mass fraction (not less)	2×10^{-4} of ^{238}Pu	3×10^{-5} of ^{238}Pu	?
mass fraction of Pu isotope oxides (not less)	95	95	-
mass fraction of actinide impurities in % of Pu total mass (not more)	-	-	1
neutron flux of a preparation containing $1g$ $^{238}Pu, c^{-1}$ (not more)	2.5×10^4	1.9×10^4	2.5×10^4



1. Metal Housing
2. Heat Insulation
3. RTH
4. Bracket
5. RTH Holder
6. Thermoelectric Converter
7. Excess heat sink
8. Mounting Bolts
9. Power Socket

Power output:	0.25 watts
Mass:	0.555 kg
Height	125 mm
Diameter	85 mm

2.10 International Situation: *RU*

- **Attempt of an analysis**
  - Rich heritage from Soviet developments
  - Only available and flight proven reactor system
    - Reason for complete halt of national use unclear (cost only?, competence/facilities no longer within Russia?)
  - Aging workforce due to stopped national programmes – decreasing institutional competence?
  - Open for cooperation
    - willingness to share core technical and technological competence (e.g on materials) questionable; lessons from TOPAZ-2 cooperation in 1990s?

2.11 International Situation: *others*

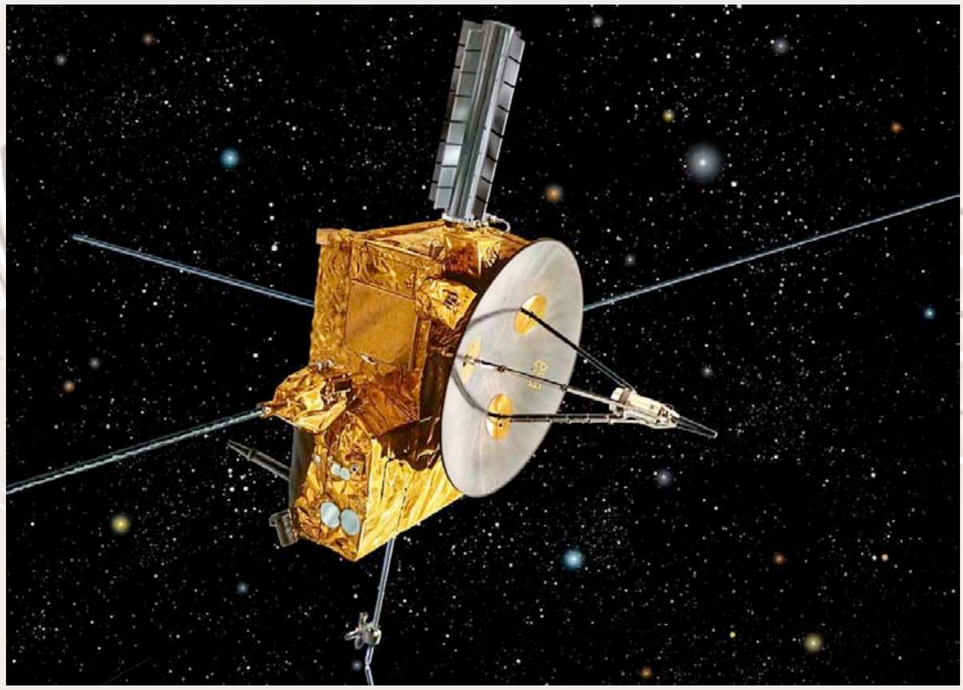
- **No information available on Japanese, Indian, Brazilian NPS activities;**
  - NPS activities within UN COPUOS are closely followed by Argentinia, Pakistan, China (in addition to traditional space/ nuclear powers)
  - Reported Japanese study on NPS in late 1980s (unconfirmed)
- **Likelihood of existing plans in China**
  - Necessary for ambitious lunar missions
  - Presence of chinese naval submarine reactors indicate adequate technological competence

3.1 European Situation

- **No industrial experience with radioisotope thermal generators or in space nuclear fission reactors;**
- **Closest industrial expertise in field of naval submarine nuclear reactors (France);**
- **Major reactor concept studies in 1980/90s: ERATO, MAPS, UKSR;**
- **Adhesion of East-European countries might change situation**
  - TOPAZ assembly plant near Tallinn, Estonia, competence remaining?
- **Use of US NPS (RTGs and RHUs) in common scientific exploration missions**
- **Recent studies on space NPS within GSP**

Cassini/Huygens spacecraft

3.2 Ulysses Spacecraft



3.3 European Situation - France

- **1983-89: ERATO programme start; feasibility of a 20-400 kWe system, 1995-97: MAPS nuclear thermal propulsion system, 300 MWth system;**
- **competence maintained (on small scale) within the CEA**
  - CNES séminaire on NPS in Sept. 2002 (~100 participants, no concrete projects).
  - There seems to be no national civil or defence project on space NPS at the moment.
- **Industrial competence from**
  - defence projects: naval reactors, CEA-*Technicatome;*
  - large civil nuclear power complex: research, logistics, maintenance, handling, security, e.g. *COGEMA*, *COGEMA Logistics,* … ;
  - propulsion system (*SNECMA*).
- **Inspection and study of TOPAZ reactor system in 1990s – abandoned, lessons learnt?**
- **Probable assessment of establishing a national RTG production in 1980/90s with negative outcome (unconfirmed)**

3.4 European Situation – *UK,D,I*

- **UK:**
  - 1987 start of UK Space Reactor (UKSR) studies, He/Xe cooled high temperature reactor; relying on "Dragon" project experience (fuel, high temperature).
- **Germany:**
  - late 1960s/beginning 1970s: first European space reactor study "*In Core Thermionic Reactor*" ; ended with US SNAP programme end;
  - academic competence available (associated industrial capacity probably partly available);
  - national nuclear exit strategy: ⇨ significant involvement of Germany in any space nuclear power sources development seems rather unlikely;
  - Option: a European (civil) space nuclear programme could provide an opportunity to continue national nuclear developments and preserve industrial nuclear research capacity.
- **Italy:**
  - Renewed interest in space NPS via Rubbia Am-242 concept; ASI involvement, significant national spending;
  - Principal decision against terrestrial nuclear power stations still valid; academic research on small scale.

3.5 European Situation – defence

- **Defence sector**
  - 1980s: studies in France and GB at least partly defence motivated (F: orbital space plane);
    no information on current projects or studies.

3.6 European Situation – *ESA*

Industrial Activities – General Studies Programme

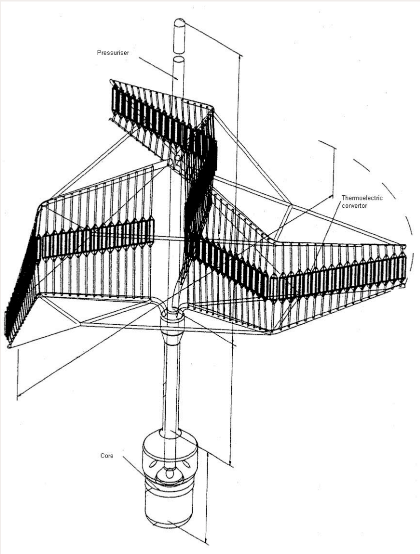
- **Reactor studies:**
  - Technicatome "Lunar Nuclear Power System (LuNPS)", 12441/97/NL/MV
    - Feasibility of a lunar surface reactor based on existing European reactor technology; highly enriched PWR; thermoelectric conversion and radiators; 10 kWe.
  - QinetiQ (subcontractors: Technicatome, AEA Techn., Serco Ass.) "Future Power Systems for Space Exploration", 14565/00/NL/WK; 2000-2003
    - Assessment of power systems for Mars exploration; Surface power reactors; NEP and NTP;
    - 2 separate reactors for propulsion and surface power
    - Development of two 50 kWe Martian surface reactor systems:
      - liquid metal – thermoelectric – radiator Technicatome design
      - gas-cooled – Brayton – CO_2-convection QinetiQ design
  - Politecnico di Milano: "Space nUclear REactor - SURE" study, 17301/03/NL/LvH, 2003
    - synergies between terrestrial and space reactors, minimum development cost approach, assessment of relevant Italian nuclear capacities
  - ESA "Propulsion 2000" programme including nuclear propulsion assessments
  - SEP-NEP study
  - "Photonic Propulsion for Interplanetary and Outer Solar System Missions" TOS-MPE study in preparation

3.7 European Situation – *ESA*

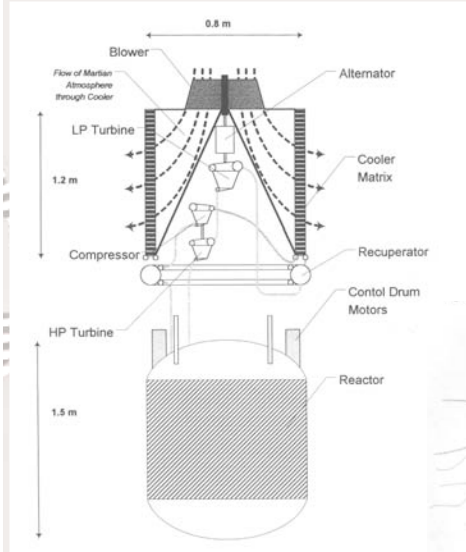
- **RTG studies:**
  - "Radioisotope Energy Storage Assessment", study by AEA Technology in 1996
  - "Radioisotope Thermal Generators for LEDA Programme", study by Krasnaya Zvezda (Ru) in 1996
    - study on the availability of Russian RTGs for the ESA lunar programme
  - "BIAPOS RTG-200", study currently under negotiation with BIAPOS (Ru)
    - study on the possibility to upgrade existing Russian small RTGs to power levels between 50 and 200 We.
- **Conversion system studies:**
  - "MHD Converters" study by Alcatel ETCA (B), Technicatome (F), LEGI CNRS (F), CSL (B) in 2002/3
    - metal gas and thermo-acoustic converters, 230kEuro
  - "Alternative Electrical Energy Generation with Thermoelectric Systems"; study by *Ecole des Mines*, Nancy

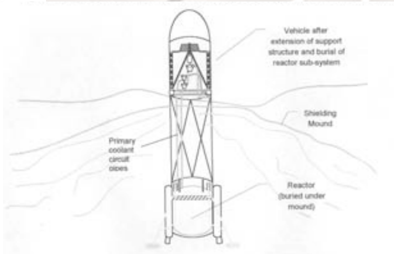
3.8 European Situation – *ESA/Industry*

Industry Reactor Designs



Liquid Metal – TE – Radiator concept
(*Technicatome*)

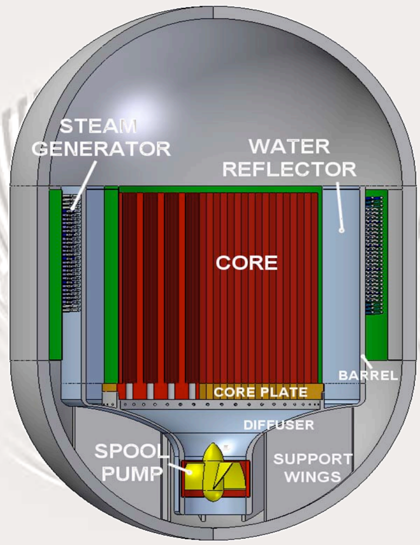




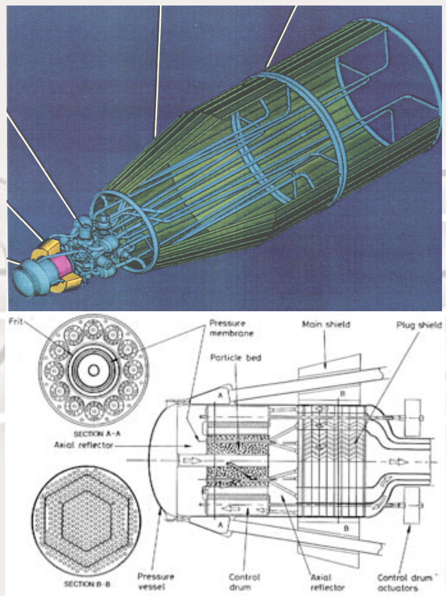
Gas cooled – Brayton – forced convection concept
(*QinetiQ*)

images QinetiQ

3.9 European Situation – *ESA/Industry*



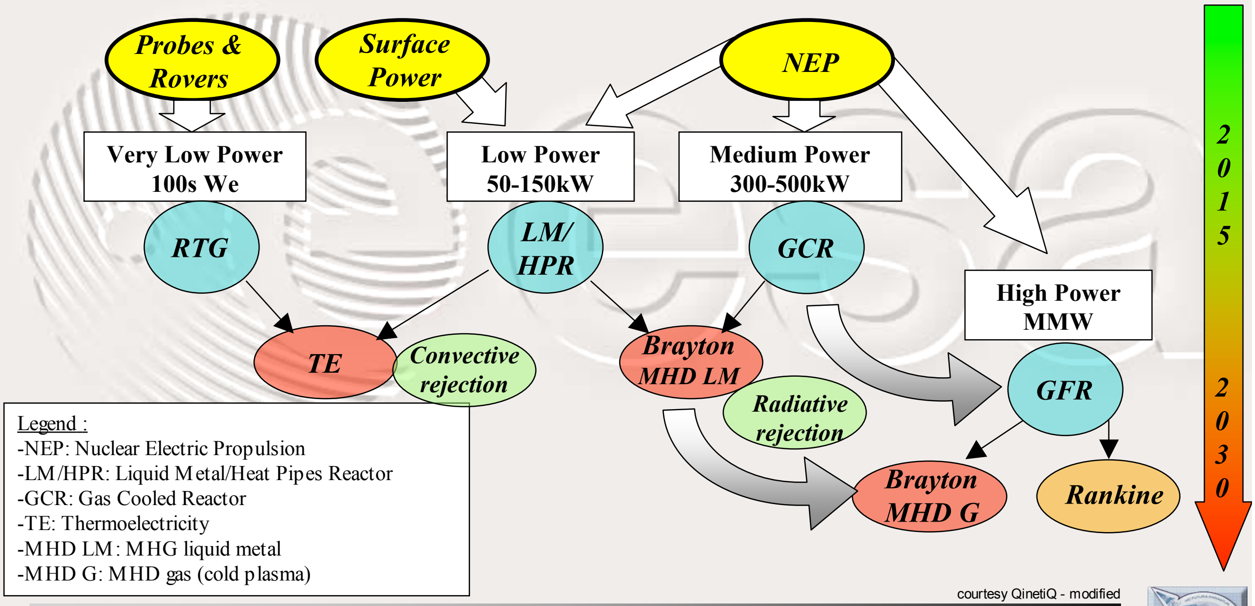
Space modified PWR – radiator
(SURE – PoliMi design))

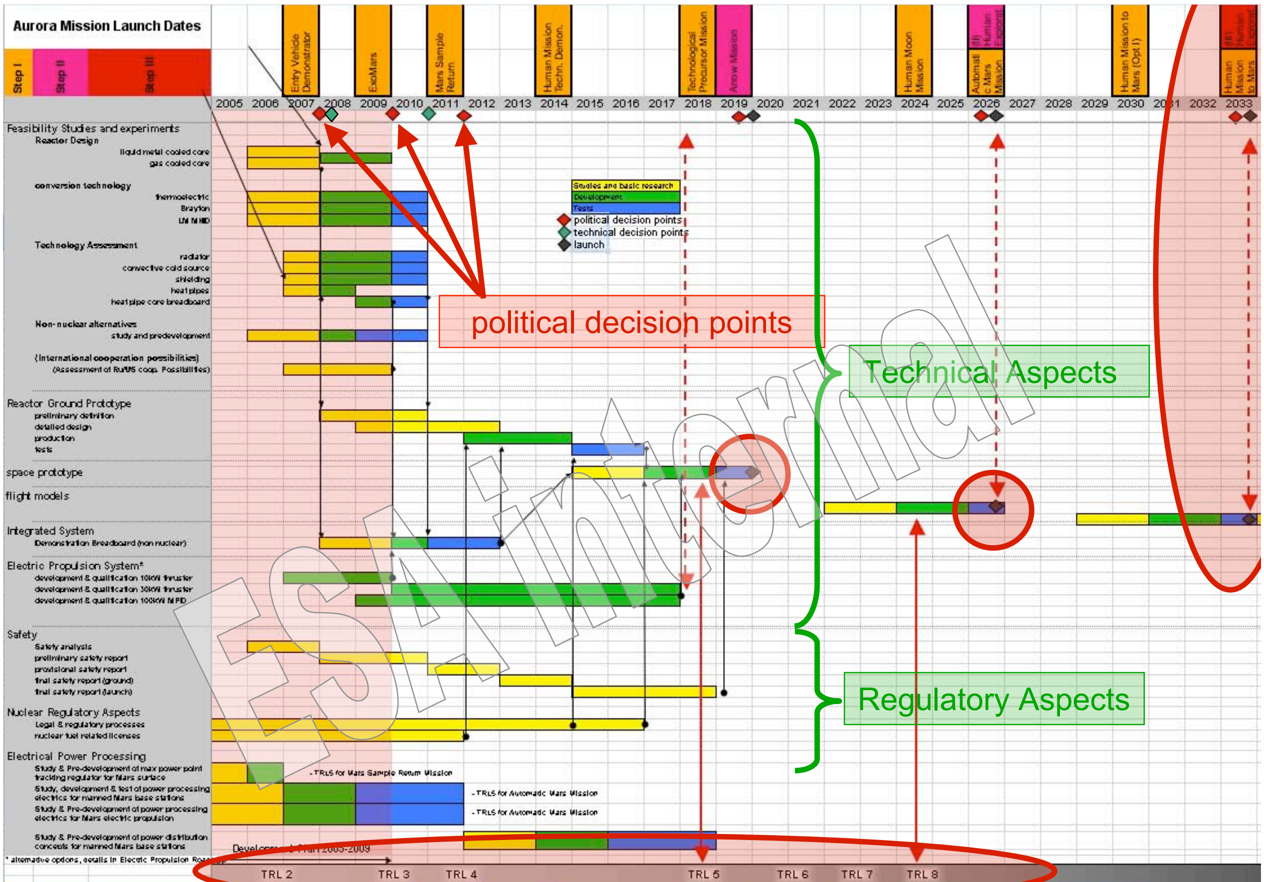


Gas-cooled – particle bed – radiator
(SNPS-200; *QinetiQ)*

3.10 European Situation – *ESA/Industry*

Industry proposed general roadmap logic





3.12 European Situation – *ESA*

ESA Internal Activities

- **Science:**
  - assessment of RTGs for different science missions
  - TRP proposal "NEP systems for outer planet missions"
- **SER (ACT):**
  - assessment of legal aspects of the use of NPS
  - assessment of administrative and logistic aspects of the use of (Russian) RTGs in Europe (*COGEMA Logistics*)
  - integration of surface reactor aspects into human Mars mission CDF study
  - participation in COPUOS NPS working group, participation in establishment of multi-year work plan
- **Recent ESA NPS meetings**
  - Jan 02: Industry/CEA/ESA meeting at ESTEC
  - Jun 03: CNES/ASI/ESA meeting at ESA HQ
  - Jan 04: ESA HQ meeting on NPS strategies
- **EC/ESA NPS WG**
  - 6 May 04: 1st meeting (establishment)
  - 30 June 04: 2nd meeting (agreement on mandate and workplan)

3.13 European Situation

- **Attempt of an analysis**
  - Principal availability of industrial and technical capacity ✓
  - Availability of independent NPS launch capability ✓
  - Long term: need of NPS for space exploration, possible "usefulness" for military space applications
  - independent development of RTGs unlikely
  - research on terrestrial nuclear reactors ongoing in Europe while halted in US for several years ⇨ respected partner
  - European decision structure possibly more favourable to long-term NPS effort than annual congressional approval system in US
  - Work on space reactors presents strong "academic attraction" (lack of young nuclear scientists)
  - Absence of an appropriate institutional frame / Absence of a European DoE/DoD/DoT
  - Assessment of "non-space" interests in NPS developments (education, high temperature materials, Gen IV activities …)

3.14 Possible European NPS Needs

European Exploration Programme:

- Robotic Mars Missions
  - e.g. ExoMars 2009:
    RHUs/RTGs for Mars rover under serious consideration (e.g. Russian supply)
    Phase B trade-off as of 2004/05
- Robotic / Human Moon missions
  - Survival of 14 Earth-days long lunar night (2020 timeframe)
- All missions beyond Mars
  - Rosetta mission: demonstration of limits of "non-nuclear" spacecraft
- Human Mars Missions (2030+ timeframe)
  - Nuclear reactors for surface stay / Mars base missions - power supply
  - Nuclear reactors to shorten transfer time - nuclear (electric) propulsion

4.1 Potential Role of EC JRC ITU

- **Relevant open questions:**
  - In case of use of Russian radioisotope sources:
    - Who owns them? Responsibility
    - Who transports them?
    - Who manipulates them? Where? What facilities are already available?
    - Who tests them? Where? What facilities are already available? Who can verify Russian test data?
    - Who licences them?
    - Who establishes the approval/licensing procedures?
    (Who plays the European DoE?)
  - Interest for these developments outside from space?

4.2 US example - repartition of tasks